CLAIMS

What is claimed is:

1. A method for use with a controller for controlling a machine wherein a torque reference value is provided, the method comprising the steps of:

obtaining feedback current values corresponding to the currents provided to the machine;

mathematically combining the feedback current values to generate an error value;

mathematically combining the error value and the torque reference value to generate a torque command value; and

using the torque command value to control the machine.

2. The method of claim 1 wherein the step of obtaining feedback currents includes obtaining d and q-axis feedback currents and wherein the step of using the torque command value to control the machine includes genrating a q-axis command voltage value as a function of the torque command value and using the q-axis command voltage value to drive the machine.

3. The method of claim 1 wherein the step of mathematically combining the error value and the torque reference value includes adding a derivative of the error value and a derivative of the torque reference value.

4. The method of claim 2 wherein the step of mathematically combining the d and q-axis feedback current values to generate an error value includes mathematically combining the feedback current values to generate a torque estimate value and subtracting the torque estimate value from the torque reference value to provide the error value.

5. The method of claim 4 further including the steps of determining the operating frequency of the machine, mathematically combining the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate and deriving a d-axis command voltage value as a function of the d-axis flux estimate and, wherein, the step of mathematically combining the feedback current values to generate the torque estimate includes combining the feedback currents and the d and q-axis command voltage values to generate the torque estimate.

6. The method of claim 5 wherein the machine is characterized by a pole count P and a stator resistance value r_s and, wherein, the step of combining to provide the torque estimate includes evaluating the following equation:

$$T_{est} = \frac{3}{2} \cdot \left(\frac{P}{2}\right) \cdot \left(\left(\frac{V_{qs}^* - r_s \cdot i_{qsfb}}{\omega_e}\right) \cdot i_{qsfb} + \left(\frac{V_{ds}^* - r_s \cdot i_{dsfb}}{\omega_e}\right) \cdot i_{dsfb}\right)$$

wherein V_{qs}^* is the q-axis command voltage value, V_{ds}^* is d-axis command voltage value, i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

7. The method of claim 2 wherein the step of using the torque command value includes the steps of deriving a q-axis command current value from the torque command value, subtracting the q-axis feedback current value from the q-axis command current value to generate a q-axis error current value, deriving a q-axis regulated voltage value from the q-axis error current value and deriving the q-axis command voltage value as a function of the q-axis regulated voltage value.

8. The method of claim 7 further including the steps of determining the operating frequency of the machine, mathematically combining the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate value, deriving a d-axis command current value from the d-axis flux estimate value, subtracting the d-axis feedback current value from the d-axis command current value to generate a d-axis error current value, deriving a d-axis regulated voltage value from the d-axis error current value and deriving a d-axis command voltage value as a function of the d-axis regulated voltage value.

9. The method of claim 8 wherein the machine is characterized by a pole count P and, wherein, the step of combining to provide the torque error value includes evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[-\frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e}\right]$$

where V_{qsreg} is the q-axis regulated voltage value, V_{dsreg} is the d-axis regulated voltage value,

i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

10. The method of claim 8 wherein the machine is characterized by a pole count P and a stator resistance value r_s, the method further including the step of deriving d and q-axis reference flux values, the step of combining to provide the torque error value including evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[\begin{array}{l} \left(\lambda_{dsref} - \frac{r_s \cdot i_{qsfb}}{\omega_e} \right) \cdot \left(i_{qs}^* - i_{qsfb} \right) - \frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \\ \left(\lambda_{qsref} - \frac{r_s \cdot i_{dsfb}}{\omega_e} \right) \cdot \left(i_{ds}^* - i_{dsfb} \right) - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e} \end{array} \right]$$

where λ_{dsref} corresponds to the d-axis reference flux value, λ_{qsref} corresponds to the q-axis reference flux value, i_{qsfb} corresponds to the q-axis feedback current value, i_{dsfb} corresponds to the d-axis feedback current value, i_{qs}^* corresponds to the q-axis command current value, i_{ds}^* corresponds to the d-axis command current value, V_{qsreg} corresponds to the q-axis regulated voltage value, V_{dsreg} corresponds to the d-axis regulated voltage value and ω_e corresponds to the operating frequency.

11. The method of claim 1 further including the steps of identifying a system operating frequency, mathematically combining the operating frequency and the torque reference value to generate a power reference value and, wherein, the step of mathematically combining to generate an error value includes combining the feedback current values to generate a power estimate and subtracting the power estimate from the power reference value.

12. The method of claim 11 wherein the step of mathematically combining the error value and the torque reference value to generate a torque command value includes the steps of combining derivatives of each of the power reference value and the power error value to generate the torque reference value.

13. The method of claim 1 wherein the error value is a power error value and the step of mathematically combining the error value and the torque reference value to generate a torque command value includes the steps of converting the torque reference value into a power reference value and combining derivatives of each of the power reference value and

the power error value to generate the torque reference value to generate the torque command value.

14. The method of claim 13 wherein the step of converting the torque reference value to a power reference value includes the step of multiplying the torque reference value by a system operating frequency.

15. The method of claim 1 wherein the controller is a field oriented controller.

16. The method of claim 1 wherein the machine is one of an induction machine, a synchronous machine and a permanent magnet motor.

17. An apparatus for use with a controller providing command voltage signals to control a machine wherein a torque reference value is provided, the apparatus for identifying an error indicative of the difference between the reference torque value and the torque applied to the machine and using the error value to modify control of the machine, the apparatus comprising:

sensors for obtaining current values corresponding to the currents provided to the machine; and

a processor running software to:

mathematically combine the current values to generate an error value;

mathematically combine the error value and the torque reference value to generate a torque command value; and

use the torque command value to control the machine.

18. The apparatus of claim 17 wherein the sensors obtain d and q-axis feedback currents and wherein the step of using the torque command value to control the machine includes genrating a q-axis command voltage value as a function of the torque command value and using the q-axis command voltage value to drive the machine.

19. The apparatus of claim 17 wherein the step of mathematically combining the error value and the torque reference value includes adding a derivative of the error value and a derivative of the torque reference value.

20. The apparatus of claim 18 wherein the step of mathematically combining the d and q-axis feedback current values to generate an error value includes mathematically combining the feedback current values to generate a torque estimate value and subtracting the torque estimate value from the torque reference value to provide the error value.

21. The apparatus of claim 20 further including a frequency determiner for determining the operating frequency of the machine and wherein the processor also runs software to mathematically combine the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate and to derive a d-axis command voltage value as a function of the d-axis flux estimate and, wherein, the processor performs the step of mathematically combining the feedback current values to generate the torque estimate by combining the feedback currents and the d and q-axis command voltage values to generate the torque estimate.

22. The apparatus of claim 21 wherein the machine is characterized by a pole count P and a stator resistance value r_s and, wherein, the processor combines to provide the torque estimate by evaluating the following equation:

$$T_{est} = \frac{3}{2} \cdot \left(\frac{P}{2}\right) \cdot \left(\left(\frac{V_{qs}^* - r_s \cdot i_{qsfb}}{\omega_e} \right) \cdot i_{qsfb} + \left(\frac{V_{ds}^* - r_s \cdot i_{dsfb}}{\omega_e} \right) \cdot i_{dsfb} \right)$$

wherein V_{qs}^* is the q-axis command voltage value, V_{ds}^* is d-axis command voltage value, i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

23. The apparatus of claim 18 wherein the processor performs the step of using the torque command value by deriving a q-axis command current value from the torque command value, subtracting the q-axis feedback current value from the q-axis command current value to generate a q-axis error current value, deriving a q-axis regulated voltage value from the q-axis error current value and deriving the q-axis command voltage value as a function of the q-axis regulated voltage value.

24. The apparatus of claim 23 further including a frequency determiner for determining the operating frequency of the machine and, wherein, the processor mathematically combines the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate value, derives a d-axis command current value from the d-axis flux estimate value, subtracts the d-axis feedback current value from the d-axis command current value to generate a d-axis error current value, derives a d-axis regulated voltage value from the d-axis error current value and derives a d-axis command voltage value as a function of the d-axis regulated voltage value.

25. The apparatus of claim 24 wherein the machine is characterized by a pole count P and, wherein, the processor combines to provide the torque error value by evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[-\frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e} \right]$$

where V_{qsreg} is the q-axis regulated voltage value, V_{dsreg} is the d-axis regulated voltage value, i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

26. The apparatus of claim 24 wherein the machine is characterized by a pole count P and a stator resistance value r_s, the processor further running software to derive d and q-axis reference flux values, the processor combining to provide the torque error value by evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[\begin{array}{l} \left(\lambda_{dsref} - \frac{r_s \cdot i_{qsfb}}{\omega_e} \right) \cdot \left(i_{qs}^* - i_{qsfb} \right) - \frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \\ \left(\lambda_{qsref} - \frac{r_s \cdot i_{dsfb}}{\omega_e} \right) \cdot \left(i_{ds}^* - i_{dsfb} \right) - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e} \end{array} \right]$$

where λ_{dsref} corresponds to the d-axis reference flux value, λ_{qsref} corresponds to the q-axis reference flux value, i_{qsfb} corresponds to the q-axis feedback current value, i_{dsfb} corresponds to the d-axis feedback current value, i_{qs}^* corresponds to the q-axis command current value, i_{ds}^* corresponds to the d-axis command current value, V_{qsreg} corresponds to the q-axis regulated voltage value, V_{dsreg} corresponds to the d-axis regulated voltage value and ω_e corresponds to the operating frequency.

27. The apparatus of claim 17 wherein the error value is a power error value and the processor mathematically combines the error value and the torque reference value to generate a torque command value by converting the torque reference value into a power reference value and combining derivatives of each of the power reference value and the power error value to generate the torque reference value to generate the torque command value.

28. The apparatus of claim 27 wherein the processor converts the torque reference value to a power reference value by multiplying the torque reference value by a system operating frequency.

29. An apparatus for use with a controller providing command voltage signals to drive a pulse width modulated (PWM) inverter linked to a machine wherein a torque reference value is provided, the apparatus for identifying an error indicative of the difference between the reference torque value and the torque applied to the machine and using the error value to modify a q-axis command voltage value used to control the machine, the apparatus comprising:

sensors for obtaining d and q-axis feedback current values corresponding to the currents provided to the machine;

an estimator for mathematically combining the d and q-axis feedback current values to generate an error value;

a torque regulator for mathematically combining the error value and the torque reference value to generate a torque command value; and

a processor using the torque command value to generate the q-axis command voltage value.

30. The apparatus of claim 29 wherein the error value is a torque error value and the regulator mathematically combines the torque error value and the torque reference value by adding a derivative of the torque error value and a derivative of the torque reference value.

31. The apparatus of claim 30 wherein the estimator mathematically combines the d and q-axis feedback current values to generate a torque error value by mathematically combining the feedback current values to generate a torque estimate value and subtracting the torque estimate value from the torque reference value to provide the torque error value.

32. The apparatus of claim 31 further including a frequency determiner for determining the operating frequency of the machine, a d-axis flux estimator for mathematically combining the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate and at least one regulator for deriving a d-axis command voltage value as a function of the d-axis flux estimate and, wherein, the estimator mathematically combines the feedback current values to generate the torque estimate by combining the feedback currents and the d and q-axis command voltage values to generate the torque estimate.

33. The apparatus of claim 32 wherein the machine is characterized by a pole count P and a stator resistance value r_s and, wherein, the estimator combines to provide the

torque estimate by evaluating the following equation:

$$T_{est} = \frac{3}{2} \cdot \left(\frac{P}{2}\right) \cdot \left(\left(\frac{V_{qs}^{*} - r_s \cdot i_{qsfb}}{\omega_e}\right) \cdot i_{qsfb} + \left(\frac{V_{ds}^{*} - r_s \cdot i_{dsfb}}{\omega_e}\right) \cdot i_{dsfb}\right)$$

wherein V_{qs}^{*} is the q-axis command voltage value, V_{ds}^{*} is d-axis command voltage value, i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

34. The apparatus of claim 33 wherein the processor uses the torque command value by deriving a q-axis command current value from the torque command value, subtracting the q-axis feedback current value from the q-axis command current value to generate a q-axis error current value, deriving a q-axis regulated voltage value from the q-axis error current value and deriving the q-axis command voltage value as a function of the q-axis regulated voltage value.

35. The apparatus of claim 34 further including a frequency determiner for determining the operating frequency of the machine, a d-axis flux determiner for mathematically combining the operating frequency and the q-axis feedback current value to provide a d-axis flux estimate value, at least one regulator for deriving a d-axis command current value from the d-axis flux estimate value, a summer for subtracting the d-axis feedback current value from the d-axis command current value to generate a d-axis error current value, at least another regulator for deriving a d-axis regulated voltage value from the d-axis error current value and deriving a d-axis command voltage value as a function of the d-axis regulated voltage value.

36. The apparatus of claim 35 wherein the machine is characterized by a pole count P and a stator resistance value r_s and, wherein, the processor combines to provide the torque error value by evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \left[- \frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e} \right]$$

where V_{qsreg} is the q-axis regulated voltage value, V_{dsreg} is the d-axis regulated voltage value,

i_{qsfb} is the q-axis feedback current value, i_{dsfb} is the d-axis feedback current value and ω_e is the operating frequency.

37. The apparatus of claim 35 wherein the machine is characterized by a pole count P and a stator resistance value r_s, the apparatus further including the step of deriving d and q-axis reference flux values, the processor combining to provide the torque error value by evaluating the following equation:

$$T_{err} = \frac{3}{2} \cdot \frac{P}{2} \cdot \begin{bmatrix} \left(\lambda_{dsref} - \frac{r_s \cdot i_{qsfb}}{\omega_e}\right) \cdot \left(i_{qs}^* - i_{qsfb}\right) - \frac{V_{qsreg} \cdot i_{qsfb}}{\omega_e} - \\ \left(\lambda_{qsref} - \frac{r_s \cdot i_{dsfb}}{\omega_e}\right) \cdot \left(i_{ds}^* - i_{dsfb}\right) - \frac{V_{dsreg} \cdot i_{dsfb}}{\omega_e} \end{bmatrix}$$

where λ_{dsref} corresponds to the d-axis reference flux value, λ_{qsref} corresponds to the q-axis reference flux value, i_{qsfb} corresponds to the q-axis feedback current value, i_{dsfb} corresponds to the d-axis feedback current value, i_{qs}^* corresponds to the q-axis command current value, i_{ds}^* corresponds to the d-axis command current value, V_{qsreg} corresponds to the q-axis regulated voltage value, V_{dsreg} corresponds to the d-axis regulated voltage value and ω_e corresponds to the operating frequency.

38. The apparatus of claim 29 further including a frequency determiner for determining the operating frequency of the machine and, wherein, the estimator mathematically combines by multiplying the torque reference value by the operating frequency to generate a power reference value, combining the feedback currents to generate a power estimate value and subtracting the power estimate value from the power reference value to generate the error value.

39. The apparatus of claim 38 wherein the torque regulator combines the error value and the power reference value.

40. A method for use with a controller for controlling a machine, the method comprising the steps of:

receiving a reference torque value;

obtaining feedback signals from the machine during machine operation;

deriving an estimate indicative of torque applied to the machine; and

controlling the machine as a function of both the reference torque value and the estimate.

41. An apparatus for controlling a machine, the apparatus comprising: sensors for obtaining feedback signals from the machine during machine operation; an estimator for deriving an estimate indicative of torque applied to the machine; and a controller receiving each of a reference torque value and the estimate and using the received values to control the machine.